Use of a Portable Programmable Guidance Display in Support of Helicopter Noise Testing

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ABSTRACT

A portable programmable guidance display (PPGD) system was adapted to support helicopter noise testing. Noise measurements using ground microphone arrays require precise flight states: position, velocity and acceleration to allow accurate data post-processing. Current noise testing and model development have introduced maneuvering flight to the test regimen, requiring repeatable, specified speed or flight path changes. Both requirements were satisfied through the use of the PPGD in a June 2006 flight test. Guidance algorithms and display features developed for civil tiltrotor and runway independent aircraft terminal area research were adapted to the noise test requirements, thus providing a new test capability.

INTRODUCTION

Rotorcraft noise, particularly during approach to landing operations, remains a barrier issue to community acceptance, impeding increased use (ref. 1). Rotorcraft noise is being addressed both by design for source noise reductions and design and by conduct of noise abatement flight operations (ref. 2). Both techniques require high fidelity noise measurement data bases to develop and verify theoretical aero-physics models and to guide empirical flight operations developments. A joint NASA-University of Maryland-Center for Rotorcraft Innovation effort aimed at collecting such data led to a flight test conducted at Moffett Field, CA, in June 2006 (ref. 3). The test featured both airborne and ground noise measurements with the requirement for precise position and maneuver control, supported by a NASA-developed programmable guidance display system.

The programmable guidance system used a pursuit guidance philosophy developed for

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14. ABSTRACT

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panel-mounted displays from a head-up display design. The underlying system has been applied to a wide range of aircraft including conventional airplane transports, V/STOL attack aircraft, and civil tiltrotor operations and control requirements studies (ref. 4, 5). From the tiltrotor application, the guidance system was adapted for use on the NASA-Army JUH-60A Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) research aircraft in support of civil terminal airspace studies (ref. 6).

The Runway Independent Aircraft (RIA) flight tests of reference 6 focused on flight path precision as a means of inserting dedicated RIA flight operations into congested terminal airspace. Flight testing aboard the highly instrumented RASCAL JUH-60A demonstrated that very precise flight paths could be hand-flown by a pilot using conventional helicopter controls with a properly tuned pursuit guidance system.

Subsequent to the RIA tests, development began toward creating a more portable version of the guidance system that could be installed in a non-experimental helicopter with minimum special equipment and no impact on the airworthiness certification of the host aircraft. Such a portable guidance system could be used to aid airspace development projects. The eventual goal was development of a briefcase-sized system that could be strapped easily into the host aircraft. The “briefcase” concept was intended for easy strap-down demonstrations of the precision pursuit guidance.

The current generation guidance system was designed as an interim step toward “portability” for use in less-augmented and less-instrumented aircraft. The current system uses a cargo pallet mounting for installation in a Bell-206 series helicopter. The PPGD system was installed in the noise test helicopter without interference to the aircraft airworthiness certification. The PPGD system provided pilot guidance for researcher-specified flight paths and flight conditions. This paper will describe the development and use of the guidance system in support of helicopter noise testing.

BACKGROUND AND MOTIVATION

Blade vortex interaction (BVI) has been identified as a principal noise source for rotorcraft. BVI involves trailing rotor blades encountering the tip vortex wake of a preceding blade. Flight conditions for BVI tend to involve positive rotor tip path plane angles of attack such as during descent or deceleration with an added impact due to reduced power operations. These conditions are most prevalent during approach to landing operations. Empirical findings embodied in the HAI “Fly Neighborly” Guide (ref. 7) and flight test and noise measurement with helicopters and the XV-15 tiltrotor research aircraft (ref. 8) suggest an opportunity to guide approach operations away from flight conditions leading to the loudest noise generation to produce noise abatement terminal area operations.

XV-15 noise measurement and noise abatement operations tests conducted in 1997 and 1999 used a simple research flight director guidance system to achieve path precision, albeit at the expense of very active pilot inputs. Those active pilot control inputs showed up as noise footprint “hot spots,” motivating guidance improvements. Similarly, a GPS-based position guidance system was developed for helicopter noise measurement testing (ref. 9), but it provided no speed guidance. An effort with an S-76 flight director (ref. 10) demonstrated what could be accomplished with a well augmented helicopter, but a more general test capability that led to smooth control inputs was still needed.

A potential solution to providing smooth, precise, path tracking resided with the

pursuit guidance philosophy. Developed for rotorcraft terminal area operations through a series of civil tiltrotor simulations (ref. 5), pursuit guidance provided the desired path precision with modest pilot workload. The pursuit display developed for tiltrotor terminal operations studies also featured speed guidance. The tiltrotor simulation development led to provision of flight director elements to aid pilot use of power and pitch attitude controls. This was of particular importance to pilots transitioning from cruise flight to slow speed approach and provided a useful cross-check for pilots not familiar with the pursuit guidance philosophy.

PROGRAMMABLE GUIDANCE DISPLAY SYSTEM

The guidance system developed for a civil tiltrotor using a flight simulator was applied to a helicopter for further development and flight research using the NASA-Army JUH-60A RASCAL helicopter. This highly instrumented and augmented research helicopter provided instrumented aircraft control positions, a research air data system, and an accurate inertial navigation system. Added to this were a programmable flight computer and display and Differential Global Positioning Satellite position sensing.

Successful application and development aboard the RASCAL research aircraft led to development of a more portable instrumentation pallet for installation on other, less instrumented aircraft. The PPGD used a laptop computer fed by inertial measurements from a package mounted on the portable pallet, GPS signals split from a GPS antenna system mounted for the test on the aircraft, air data from a separate research air data boom, and collective stick position from an infrared sensor mounted near the collective, but not interfering with that control motion. The computer and inertial platform were mounted on a pallet that mimicked the footprint and mounting of a standard Bell cargo platform.

The research PPGD pallet, shown in Figure 1, could be mounted in the cabin of either an OH-58 (used for prototype development) or Bell 206 (used for the noise test). Shown is the top shelf of the two-shelf cargo pallet mounted in the test aircraft. The lower shelf mounted a GPS-enabled inertial platform and power supplies. The top shelf had a mounting for the laptop computer at the core of the PPGD system. Additional mounting brackets provided secure mounting for acoustic measurement gear and other test apparatus.

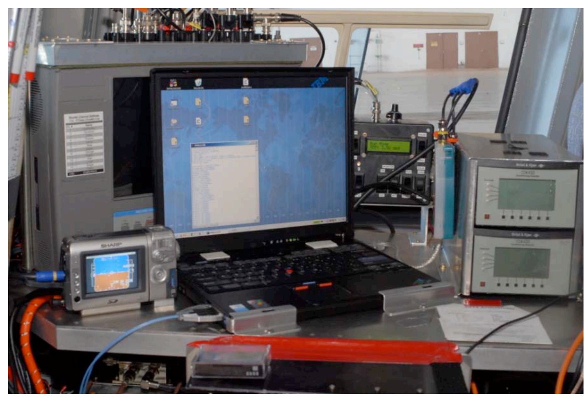

Figure 1. Portable Programmable Guidance Display components on aircraft pallet.

Figure 2 shows a system operator interacting with the computer as mounted in the aircraft. This computer received sensor inputs, from the inertial platform, air data boom and the collective sensor (shown in figure 3 and described below). The guidance code in this computer processed this data and generated the pilot display which was presented to the pilot on a cockpit-mounted display unit, as seen in figure 4. The laptop computer also served as the repository of all airborne data collected. The system operator managed the airborne data files and loaded each test

profile as required by the test card and test director.

Figure 2. System operator interacting with airborne computer.

Collective Sensor

Collective stick position was used in the guidance algorithm of the PPGD. Original developments of the system occurred on aircraft with stick position sensors as part of their experimental data packages. The goal of the PPGD development was a guidance package that could be strapped into an aircraft without disturbing the basic airworthiness. Such an application required a collective stick position sensor that did not interfere with control system movement or even create a suggestion that that might be an issue.

Collective stick position was measured using a floor-mounted infrared sensor which reflected off a plate taped to the collective stick as shown in figure 3. Care was taken to ensure this mounting did not interfere with control movement. A flat reflector was used although other shapes were tried in an attempt to reduce hysteresis in the stick position calibration curve. Further work on reflector shape will be done for future uses.

Figure 3. Collective lever with non-intrusive reflector on stick and floor-mounted infrared position sensor.

Guidance provided by the PPGD was displayed on a supplemental display mounted atop the cockpit panel, as seen in Figure 4. The display was approximately 6 inches high by 8 inches wide and mounted such as to minimize its impact on the pilot's field of view. Much of the area behind the display would be obscured otherwise by the windshield center support.

Figure 4. PPGD display on cockpit panel.

Pursuit Guidance Display

The cockpit display used a primary flight display format inspired by current transport aircraft electronic displays. As shown in figure 5, airspeed and altitude tapes flank a central display area that provides attitude indication with a positive angles pitch

ladder, horizon line and fixed aircraft "wing" reference (facing white "L"shapes).

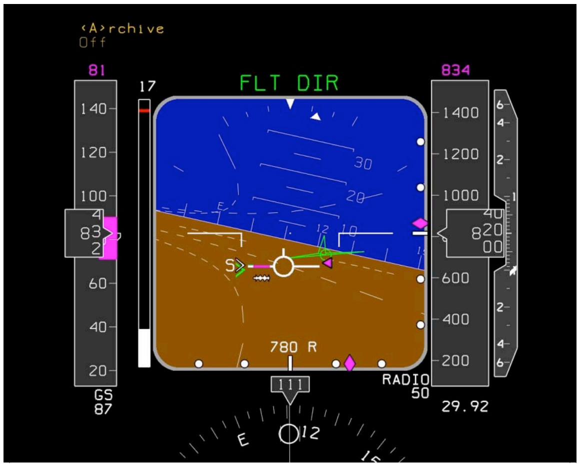

Figure 5. Primary guidance display format.

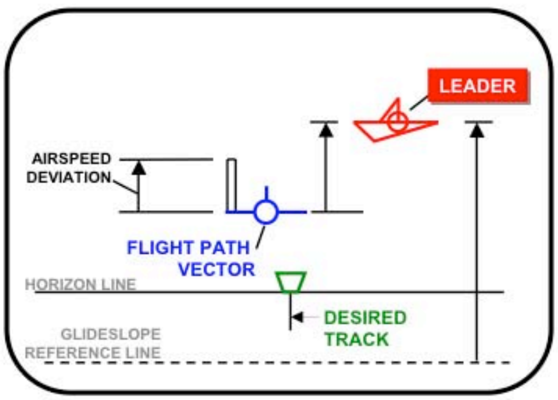

Figure 6. Pursuit display elements.

As shown in figure 6, the central elements of the pursuit guidance philosophy are the own-ship flight path vector, seen as winged circle (white in fig. 5) and a leader aircraft, shown as a delta-winged symbol with a vertical tail (green in fig. 5). The leader aircraft symbol "flies" a perfect path, programmed into the guidance. The track error of the own-ship is seen as the offset of the own-ship symbol from the leader. Raw deviation from the perfect path also shows as magenta markers arrayed for vertical error on the right side of the central display area and lateral deviation on the bottom. The pilot task is to manipulate the aircraft controls such as to drive the own-ship symbol to overlap the leader, much like formation flying, hence, the pursuit philosophy. With the own-ship symbol overlaying the leader, the aircraft will converge onto the perfect path. This convergence onto the desired path tends to produce smooth flight operations, critical to the noise measurement task. The entire display conforms to a perspective view of the world, as might scale up to an out-the-window view. Guided in this fashion, a pilot can achieve very precise position (path) tracking with minimum, modest control inputs. An advantage over traditional compensatory flight directors is the greatly reduced development effort required to achieve the desired smooth and precise tracking of the designated path.

Speed guidance is provided both as a command setting in the form of the magenta tab on the airspeed tape on the left side of the display and via additional symbols around the own-ship flight path symbol. Both pitch attitude and collective position directors are provided using compensatory drive laws, typical of a flight director. Adding the compensatory director elements was viewed as a "crutch," but was found useful in the civil tiltrotor terminal area research (refs. 4 & 5). The pitch attitude director is provided by the displacement of a magenta carat relative to the right wing tip of the own-ship symbol in figure 5. A nose-up command is provided by a displacement of the carat above the own-ship symbol wing. Additional speed information is provided by an acceleration symbol set (green carat and "S") on the left side of the own-ship symbol. Reference 5 discusses how this symbol set functions. A collective flight director is provided via the hand grip seen displaced below the left wing of the own-ship symbol in figure 5. This displacement of the collective director "grip" symbol provides an "add collective" indication. The pair of control directors

augments the flight state and flight path guidance provided by the primary pursuit elements.

Introduction to use of the pursuit guidance system requires training and adaptation, but the tracking results obtained can be quite remarkable. For the helicopter noise test, a further challenge was the use of a commercial helicopter pilot with considerable B206 experience but with limited instrument flight experience. Familiarization training was provided for the pilot using a desk-top simulation workstation. The workstation training focused on familiarization with the guidance format and sample test operations. The pilot spent over twenty hours in ten training sessions familiarizing himself with the guidance display and the test operations. At the end of the training period, both he and the test team were satisfied with his use of the guidance to achieve the desired path precision and speed tracking.

HELICOPTER NOISE TEST

The helicopter noise test conducted at Moffett Field in June 2006, had objectives of:

1. Collecting noise measurements during maneuvering flight. Flight maneuvers included accelerations and decelerations on designated flight paths and circles performed as turns about a point on the ground.
2. Collecting simultaneous noise measurements for correlation using a ground microphone array and an airborne array mounted on a spray boom rig on the helicopter.
3. Using the NASA PPGD guidance to perform precise flight paths and repeatable maneuvers.

An overview of the acoustics results of the test is provided in reference 3.

The test was flown using a B206 helicopter equipped with a spray boom rig for the airborne microphone array, an experimental air data boom, a tip path plane position sensor (reference 11), and the NASA PPGD. Figure 7 shows the test aircraft over-flying one of the ground microphones. Figure 8 shows two of the boom-mounted microphones. The ground microphone array used microphones mounted in the center of ground boards with a nearby tripod-mounted air data system and transmission antenna for wireless connection to the data collection system. A winch-driven, balloon-lifted, radiosonde, shown in figure 9, provided a continuous survey of winds up to 1000 feet AGL.

Figure 7. Bell Model 206 Test helicopter.

Figure 8. Boom-mounted microphone.


Figure 9. Winch-driven radiosonde and balloon.

Test Matrix

The helicopter noise test matrix featured three distinct flight operations types: steady flight at constant airspeed and fixed flight path angle (level or descent), straight descending accelerated and decelerated flight, and turns. Guidance code was developed for all three, though final implementation of circle guidance was deferred to a subsequent test. The top speed tested was 75 knots, based on aircraft performance and providing a wide margin below the spray boom rig limit speed of 86 knots.

The steady conditions test matrix incremented airspeed between 40 and 75 knots and flight path angle from level flight to descents as steep as fifteen degrees. Data from the steady condition test matrix will be used to construct noise radiation hemispheres for use in the Rotorcraft Noise Model (ref. 12). Primary airspeeds tested were 50, 60 and 70 knots. The initial speed and descent angle survey identified a noise hot spot with high BVI sound levels at 60 knots and 7.5 degrees descent. Subsequent test cards used this as a center point for more detailed speed and flight path angle surveys and for the straight descents with acceleration or deceleration.

One of the important features of this helicopter noise test and the use of the PPGD was the provision of guidance to fly constant accelerations or decelerations. Previous rotorcraft noise testing showed the ability to alter the noise level using unguided decelerations or accelerations (ref. 13). While the flight path guidance assured steady flight path tracking, the PPGD speed guidance was programmed to provide constant, selected decelerations and accelerations. Accelerations of 0.05, 0.1 and 0.15 g and decelerations of 0.05, 0.1, 0.15, and 0.2 g were provided for. The importance of wind gradient effects translating to acceleration or deceleration was described in reference 14. The current test marked the first use of guided, repeatable, descending accelerations and had the good fortune of calm winds.

Guidance Profile

The PPGD uses guidance algorithms based on runway coordinates—where the origin is an arbitrary point in three-space, usually of some significance to the test, such as the intended landing spot. For the purpose of the helicopter noise test, the runway coordinate origin was established at the center of the ground microphone array, with the X-axis oriented perpendicular to the array (positive forward). The Y-axis was oriented along the microphone array (positive-right). Flight path position and angle and speed profiles were mathematically described based on those coordinates, with flight path X-distance as the independent variable. Separate profiles were provided for height and flight path angle, lateral track (Y-distance) and speed. Speed profiles could use either inertial reference (ground) speed or airspeed from the air data boom.

The standard profile set developed for this test involved a downwind guidance capture, base turn, a steady level segment prior to glide slope capture, and descent at the specified flight path angle. All descending paths crossed the microphone array at 250 feet above ground level (AGL). Level flight speed sweeps crossed the array at 150 feet. Standard test procedure had the aircraft continue the descent beyond the microphone line to a data-off point at 150 feet AGL. After initial testing, the center of the deceleration and acceleration segments was established at -1000 feet, before the microphone array line. This was selected by the acoustics researchers to best capture the BVI noise impact of the acceleration or deceleration.

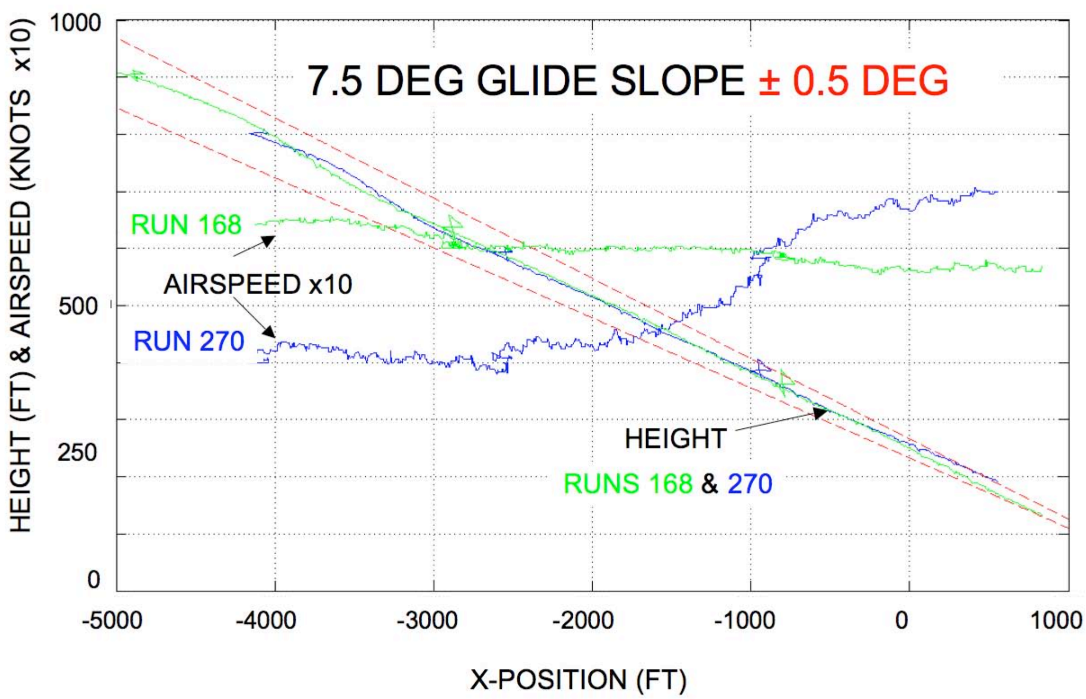

Figure 10. Height and Velocity versus longitudinal path position for a steady state descent (run 168) and an accelerating descent (run 270).

FLIGHT TEST RESULTS

Flight path position (height and lateral error) and velocity tracking results were collected and analyzed for the steady condition testing, decelerations and accelerations on glide slope. The data was analyzed over the prime data range from 2500 feet before crossing the microphone line to 500 feet beyond the microphone line. For many runs, data collection was terminated before reaching the point 500 feet beyond the microphone line. This allowed the pilot to safely and easily recover from the steeper descents and begin climbing back for the next data point. Flight test results were analyzed both for individual runs and subsequently gathered together for statistical analysis.

Examples of the precision obtained during the test are shown in figure 10. Shown in this plot are vertical flight path and velocity tracks for a steady speed descent (run 168) and an acceleration on glide slope (run 270). Both runs used a 7.5 degree descending flight path which provided high BVI noise for the steady speed case flown at 60 knots.

Tracking Error Results

Statistical analysis was performed on the flight path and velocity tracking data. For this purpose, the steady speed descents were collected into a single analysis ensemble with just the data from the prime data range from -2500 to +500 feet, along the longitudinal path. Similar data analysis ensembles were collected for the descending deceleration cases and the descending acceleration cases. Composite plots of all data in each ensemble were created and mean and standard deviation calculated for those data.

Steady Speed Descents

Fifty-three steady descent runs were judged useable by the test team. This judgment considered accuracy of tracking flight path position and airspeed as well as smoothness of control activity, a key value judgment for noise testing. As seen in previous rotorcraft noise testing, abrupt control movements lead to brisk changes in rotor angle of attack, negating the quasi-static assumption of the testing and subsequent noise radiation analysis. Composite plots containing data from all fifty-three steady descent data runs are shown in figures 11-13. These plots show height, lateral position and airspeed tracking error as a function of flight path longitudinal range (horizontal distance along the flight path).

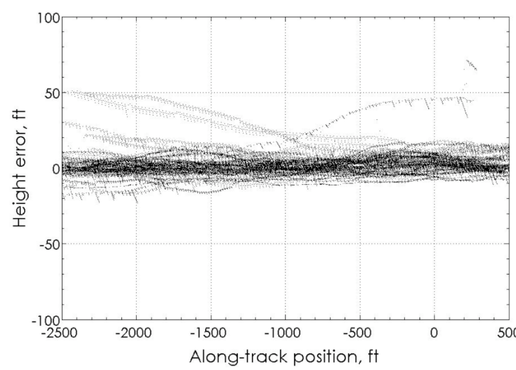

Figure 11. Height tracking error versus path longitudinal distance for steady descents.

Height tracking error is shown in figure 11 for the steady descent cases. The mean error for this data has a slight bias of 2.43 feet above the commanded path. The standard deviation is 8.4 feet. Put another way, the aircraft was flown within 17 feet of the desired flight path 96% of the time for these runs.

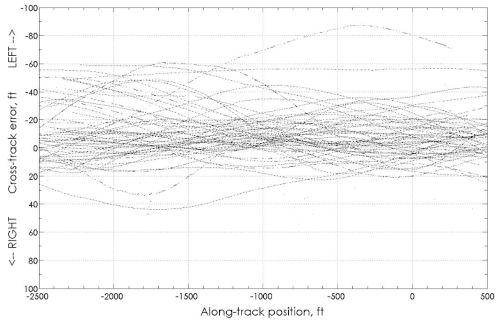

Figure 12. Lateral tracking position error versus path longitudinal distance for steady descents.

Lateral tracking error is shown in figure 12 for the steady descents. Note for this figure and subsequent lateral error figures that the axis system is oriented for an observer above the aircraft, looking down. Left of track (negative Y) is shown in the upper half of the figure. The aircraft wandered laterally much more than in height. Both the guidance system sensitivity and pilot-vehicle system response were looser laterally than vertically. Historically, lateral guidance sensitivity has been set about half that used for vertical error for instrument guidance such as the PPGD. The reduced lateral guidance sensitivity combined with looser following of the guidance by the pilot and the aircraft's ability to maintain lateral tracking resulted in the lateral tracking error presented in figure 12. The mean lateral tracking error was 9.67 feet to the left of centerline. Standard deviation was 18.5 feet, a bit more than double the vertical tracking result.

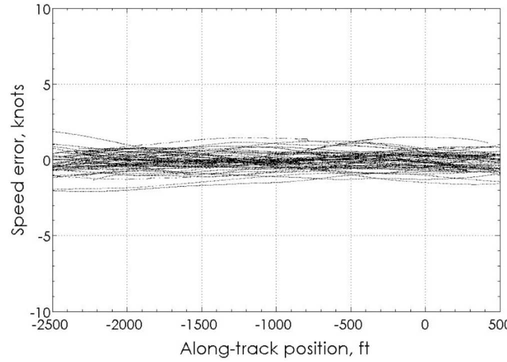

Figure 13. Airspeed tracking versus path longitudinal position for steady descents.

Airspeed tracking for steady speed descents is shown in figure 13. Airspeed tracking was very good with a nearly neutral mean and a standard deviation of 0.6 knots. Further, detailed examination of the individual data run airspeed plots shows the slight airspeed variations were very smooth, providing the data desired for acoustics measurements.

Decelerating Descents

Constant decelerations were commanded on fixed descending flight path angles. The commanded decelerations were initiated before the microphone line such that they ended as the aircraft crossed the microphone line. Twenty knot decelerations were commanded from 70 knots down to 50 knots. The guidance system used a speed versus path longitudinal position formula for the deceleration segment. Flight path tracking and speed error results were collected and analyzed for fifteen runs.

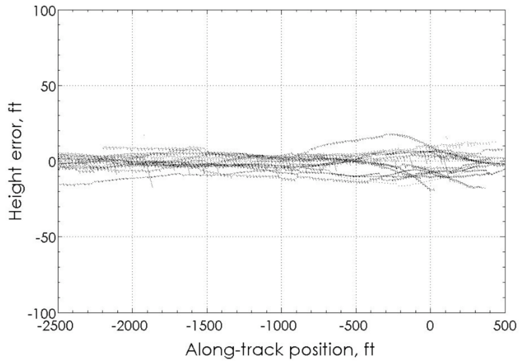

Figure 14. Height tracking error versus path longitudinal distance for decelerating descents.

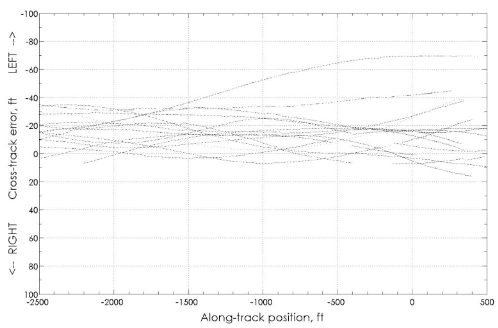

Figure 15. Lateral tracking position error versus path longitudinal distance for decelerating descents.

Height tracking error versus path longitudinal distance is plotted for the deceleration cases in figure 14. The height error has a slight bias downward with a mean of 1.5 feet below path. The height error standard deviation was 6 feet, reflecting very good, consistent, height tracking. Lateral position tracking error is plotted in figure 15 for the descending decelerations. The deceleration case lateral tracking results were similar to the steady airspeed cases with a bit more left of track bias (mean of 16.6 feet) and a similar standard deviation of 14.7 feet.

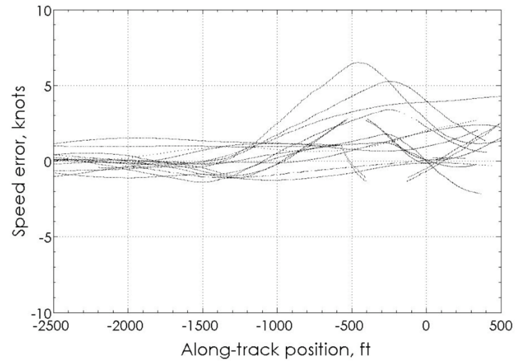

Figure 16. Airspeed tracking versus path longitudinal position for decelerating descents.

Speed tracking error is shown plotted versus longitudinal path position in figure 16 for the deceleration cases. The speed tracking error begins building when the deceleration command begins, typically around 1000 feet before the microphone line. Pilot comments and observation of this tracking performance suggested a need for an alert to the pilot just prior to the start of the deceleration segment.

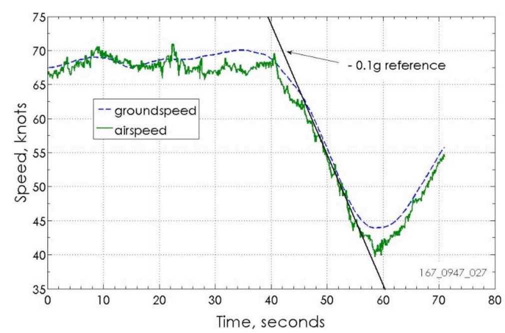

Figure 17. Airspeed and ground speed versus time for a deceleration case.

In spite of the airspeed error shown in figure 16, good test results were obtained. Figure 17 shows airspeed and ground speed plotted versus time over the deceleration segment. A reference 0.1g deceleration is shown in the figure. In spite of the pilot-vehicle system lagging behind the commanded velocity profile, a good segment of steady deceleration was

obtained. Also note that air and ground speed are nearly identical, a testament to the calm conditions prevalent for this test.

Accelerating Descents

Acceleration while descending was tested for several acceleration values. This is a counter-intuitive operation for pilots as virtually all of their flight training and experience features either constant speed descents or deceleration on the final approach path. Acoustic theory suggested a acceleration might offset the angle of attack effect of the descent. If proven out, descending accelerations might provide a flight operation tool for mitigating the additional noise impact of some descent segments.

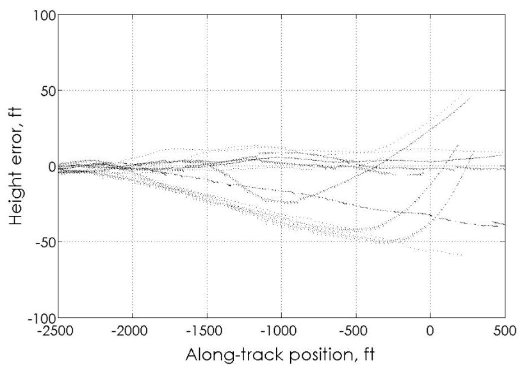

Figure 18. Height tracking error versus path longitudinal distance for accelerating descents.

Eleven acceleration while descending cases were analyzed. Figure 18 shows the height tracking error for these cases. About half the cases show consistent, on glide slope tracking. Most of the other cases show descent below the commanded flight path. Acceleration requires pitching the aircraft nose-down. If not countered by an appropriate addition of collective pitch (power), the aircraft will descend below the commanded path, as shown here. As seen in figure 18, most of these cases provide smooth, straight error segments. This translates to a steeper flight path angle than commanded, but still steady such that good acoustic measurements still resulted, albeit not quite at the commanded flight path angle.

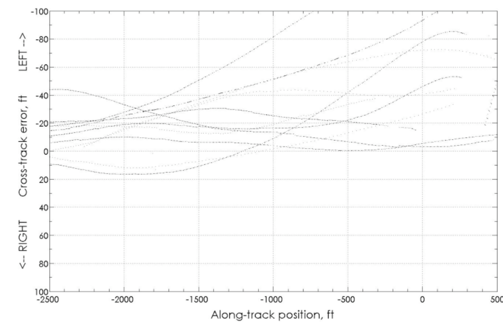

Figure 19. Lateral tracking position error versus path longitudinal distance for accelerating descents.

Lateral tracking error is shown as a function of longitudinal path position in figure 19 for the eleven descending acceleration cases. Lateral position tracking was worse for these cases than the steady or decelerating descents, suggesting the pilot was more concerned with trying to maintain speed and height than lateral position. The lateral tracking error mean was 27.4 feet to the left and had a standard deviation of 28.8 feet for these descending acceleration cases. This was about double the error of the steady and decelerating cases.

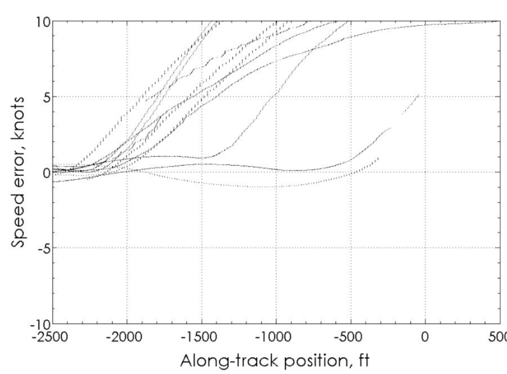

Figure 20. Airspeed tracking versus path longitudinal position for accelerating descents.

As with the descending decelerations, the descending accelerations were commanded via a speed versus longitudinal position profile in the guidance system. The accelerations were commanded from 50 to 70 knots, ending about the time the aircraft crossed the microphone line. Figure 20 shows the speed error versus longitudinal path position. As with the decelerations, the speed error grew as soon as the acceleration segment began. As with the decelerations, pilot comments and observation recommends an alert from the guidance system prior to the initiation of the acceleration segment.

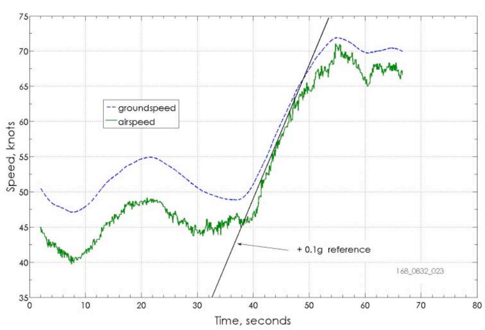

Figure 21. Airspeed and ground speed versus time for an acceleration case.

Figure 21 shows a plot of airspeed and ground speed for an acceleration segment, demonstrating results similar to the deceleration cases. Although the pilot-vehicle system lagged the airspeed command profile, an acceptable segment of constant acceleration was achieved.

CONCLUSIONS

1. A portable programmable guidance display system previously developed for airspace operations studies was adapted to support helicopter noise testing. Flight test results from a June, 2006, test using a Bell 206 helicopter showed that precise, smooth data runs were achieved using the guidance system.

2. Guidance profiles were developed and used for steady descents, decelerating descents and accelerating descents. The addition of speed guidance to position guidance provided a new tool for acoustics measurement testing.

3. The test provided additional data for validation of acoustic theory suggesting a noise reduction with acceleration on descent. Acceleration on descent is a counter-intuitive operation for most pilots. Flying with the aid of the guidance system produced useful time segments of steady acceleration at precise flight path angles.

4. Analysis of test results shows the need to improve lateral tracking precision.

The PPGD will be developed further to support helicopter noise research. Guidance for circles will be implemented for future tests. Further development of the collective stick position sensing will be done to reduce the hysteresis experienced. Non-intrusive stick position sensors will be developed to assist flight dynamics data analysis and provide potential additional inputs to the guidance system.

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